A NEW VERSION OF THE SNOWMELT RUNOFF MODEL INCORPORATING RADIATION

Kaye L. Brubaker
Department of Civil Engineering, University of Maryland, College Park, MD 20742

Albert Rango
USDA Hydrology Laboratory, Bldg. 007, Room 104, Beltsville, MD 20705

Abstract. As a microcomputer program with modest data requirements, the Snowmelt Runoff Model (SRM) has been successfully applied to simulate and forecast runoff from seasonally snow-covered basins around the world. The existing SRM uses the Temperature Index method, a single-index equation based on daily temperature, to predict snowmelt runoff. Recent work to enhance SRM has added a second index, net radiation, to create a more flexible and physically-based version known as the Temperature/Radiation method. Both SRM versions use an index equation to compute snowmelt runoff from the snow-covered fraction of a basin, and can incorporate remotely-sensed data to determine the physical parameters required for model input. This paper compares the results of the Temperature Index and Temperature/Radiation methods with observed runoff from (1) a small basin with measured net radiation, (2) a small basin with net radiation estimated from in-situ meteorological measurements, and (3) a large basin with net radiation estimated using publicly available data from on-line sources. The results show that the two versions are comparable in terms of the computed numerical measures of model performance. Therefore, the user could choose between the two methods depending upon the available data. The Radiation/Temperature method reduces the need to vary a critical model parameter throughout the season, and provides a physically-based method to estimate that parameter independent of model output.

INTRODUCTION

In many regions of the world, the runoff produced by the melting of seasonal snowpack in nearby mountain ranges represents a significant contribution to regional water resources. The mountain snowpack functions as a natural reservoir; it accumulates water in the form of snow during the winter and releases it in liquid form during the warm season, when the water can be used for hydropower, irrigation, or municipal water supply. Melt-season floods can also represent a significant hazard in some regions. Whether snowmelt is seen as a resource or a risk, the ability to forecast the quantity and timing of melt-season runoff is of great value to society. A number of mathematical models, spanning a range of complexity, have been developed for use in forecasting and for detailed study of the physical processes involved in snowmelt and runoff production; Kirnbauer et al. (1994) summarize the current state of snow modeling.

The Snowmelt Runoff Model (SRM) is used worldwide for forecasting melt season runoff in mountain regions. The model has been applied in mountain basins ranging from 0.76 to 120,000 km^2 in area. The procedure is initialized with a known or estimated discharge value and can proceed for an unlimited number of days, as long as the input variables (temperature, precipitation, and snow-covered area) are provided. First developed in 1975, SRM has been implemented for microcomputer, and has undergone refinements bringing it to Version 3.2 (Martinec et al., 1994). Owing to its simple data requirements and the use of remote sensing to determine snow-covered area, SRM is ideal for use in regions where surface data are sparse (Kumar et al., 1991).

SRM is currently undergoing development to improve the physical basis of its model components, and to make it more useful in predicting the hydrologic effects of possible large-scale climate change. Version 4.0, incorporating year-round climate change effects into the Temperature-Index version, is currently being beta-tested (http://hydrolab.arsusda.gov/cgi-bin/srmhome). In parallel, a new version of SRM has been developed, incorporating radiation in addition to temperature for calculating snowmelt; this new version is the subject of this paper.

METHODOLOGY

A snowmelt runoff model must accomplish two basic steps. First, it must estimate the volume of water produced by melting snow in a given period of time. Second, it must route that water through the hillslopes and stream network of the basin to the point of interest (the basin outlet, a reservoir, or a hydroelectric dam, for example).

The energy to melt snow is supplied by radiation and by the turbulent exchange of sensible and latent heat with the near-surface air. The radiative and turbulent terms of the energy balance are controlled by different physical factors. The flux of shortwave (solar) radiation into the snow is a function of time of year, surface geometry, atmospheric transmissivity, cloud cover, and the reflectivity (albedo) of the snow itself. The longwave radiation into the snow depends upon the temperature and humidity profiles in the overlying atmosphere,

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as well as cloud type and cover. The rate of turbulent energy transport, by contrast, depends upon near-surface properties such as wind speed, atmospheric stability, and the gradients of temperature and humidity.

Two Versions of the Snowmelt Runoff Model

Versions 3.2 and 4(beta) of SRM use a Temperature Index (degree-day) approach to estimate the volume of melt. Daily-average near-surface air temperature is an integrated measure of the overall energy exchange during the day; in addition, air temperature has been shown to be best single meteorological variable for predicting snowmelt (Zuzel and Cox, 1975). Because temperature is strongly dependent upon elevation, the basin is subdivided into Hydrologic Response Units (HRUs) based upon elevation, and melt is estimated separately for each HRU. In the Temperature Index method, the meltwater contribution from the snow-covered portion of the HRU is computed as proportional to the temperature (degree-day) index,

$$M = a\, T_d \qquad (1)$$

where M is the daily melt volume (expressed as water depth, cm) from each unit area of the snow-covered fraction of the zone, T_d °C day is the degree-day index and a (cm °C^{-1} day^{-1}) is the degree-day coefficient. The degree-day index is equal to the daily-average temperature, if it is above 0°C, and zero otherwise. Detailed empirical studies with snow lysimeters have shown that the coefficient a increases through the melt season (Martinec, 1989).

The goal in developing the Radiation/Temperature method is to improve SRM's physical basis, ultimately making it more useful for forecasting and investigations of climate change effects. In this approach, the radiative and turbulent transport energy contributions are treated separately. Meltwater volume is computed by summing a contribution proportional to the degree-day index and a contribution proportional to a net radiation index (R_d) for each HRU,

$$M = a_r\, T_d + m_Q\, R_d\,. \qquad (2)$$

In Eq. (2), a_r (cm °C^{-1} day^{-1}) is the restricted degree-day coefficient, which is not equal to a in Eq. (1), but multiplies the same degree-day index, T_d. The magnitude of a_r reflects the efficiency of turbulent transport, including wind speed and atmospheric stability. The net radiation index R_d has the dimension of energy flux density (W m^{-2}); and m_Q [cm (W m^{-2})$^{-1}$] is a physical constant converting energy flux density to water mass expressed as depth. For this method, the basin may be further subdivided by general orientation (aspect), because solar radiation to a surface is strongly dependent upon orientation. Thus, the HRUs for the Radiation/Temperature method are elevation-aspect zones, rather than simply elevation bands as in the Temperature Index method.

The coefficients multiplying T_d in the two different melt estimation methods are not identical. The restricted degree-day coefficient a_r in Eq. (2) is smaller than a in Eq. (1) because the radiation term $m_Q R_d$ in Eq. (2) accounts for a portion of the energy available for melt, whereas in Eq. (1) the product aT_d must account for all the energy sources.

In both versions of the model, the daily meltwater contribution and rainfall from each HRU are combined, then partitioned into immediate runoff and baseflow according to a recession parameterization. The recession and parameters are estimated from streamflow records for the basin as described by Martinec et al. (1994).

Both versions require spatial data (basin and HRU area, area-elevation curve), and time-series data (observations or forecasts of daily average temperature, precipitation, and snow-covered area for each day of the period to be modeled). The Radiation/Temperature method requires additional daily meteorological data: atmospheric pressure, relative humidity, and a measure of cloudiness (either cloud fraction or hours of sunshine, or both). Besides the runoff routing parameters common to both versions, the Radiation/Temperature method requires two additional parameters for computing the cloud effects on shortwave (solar) and longwave radiation.

The parameters required by SRM are not determined by optimization. Rather, the user is guided in evaluating these parameters from basin flow records, additional data, and physical reasoning. Empirical methodology exists to estimate a from snow density measurements (Martinec et al., 1994) and a method has been published for estimating a_r from meteorological data, based on a simplified equation for energy transfer between the snow and near-surface air (Brubaker et al., 1996).

The net radiation index R_d in Eq. (2) is set equal to the daily net radiation (R_{net}) if R_{net} is greater than zero, and to zero otherwise,

$$Rd = \max[R_{net}, 0] \quad [W\ m^{-2}] \qquad (3)$$

where daily net radiation is calculated as follows:

$$R_{net} = K_{in} - K_{ref} + L_{in} - L_s \qquad (4)$$

in which $K_{in,ref}$ refer to the incident and reflected shortwave (solar) radiation, and $L_{in,s}$, respectively, to the longwave radiation emitted by the atmosphere and by the snow surface. The Radiation/Temperature version allows R_{net} to be entered directly as input data (if available) or estimated from routine meteorological measurements.

Model Performance Criteria

The SRM microcomputer program calculates two measures of simulation accuracy: the coefficient of determination R^2 and the volume difference D_v. R^2 is computed as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q_i')}{\sum_{i=1}^{n}(Q_i - \overline{Q})} \tag{5}$$

where Q_i and Q'_i are the measured and computed daily discharge, respectively, $\overline{Q}$ the average measured discharge for the given year or melt season and n the number of daily discharge values. The volume difference D_v is defined as

$$D_v\,[\%] = \frac{V_R - V_R'}{V_R} \times 100 \tag{6}$$

where V_R is the measured and V_R' the computed yearly or seasonal total runoff volume. A non-zero D_v may result from errors in the model input or parameters, or physical factors such as spatial variability of the physical quantities, which the model assumes to be uniform over each HRU. Due to the uncertainties in measurement and extrapolation or interpolation of physical quantities, errors in the model input are unavoidable. If these errors are random, then it is reasonable to expect that, over a number of different years or seasons, the values of D_v for the different simulations will scatter around zero, although D_v may be either positive or negative for a given simulation.

Tests of the Radiation/Temperature Version

The new radiation/temperature version of SRM has been tested on (1) the W-3 subbasin of Sleepers River, Vermont where measured net radiation data were available; (2) the Dischma basin in the Swiss Alps, where net radiation was estimated from in-situ meteorological measurements at a nearby mountain research station; and (3) the Upper Rio Grande in Colorado, for which net radiation was estimated using publicly-available data from US weather stations. These basins were selected because they have all been successfully simulated with the Temperature Index version of SRM, and all the required model parameters are in place, having been determined through hydrologic expertise, knowledge of the basins, and the guidelines in Martinec et al. (1994). In all three cases, the two versions of SRM were compared in simulation (hindcasting) mode.

Sleepers River, Vermont, USA

The W-3 sub-basin of the Sleepers River Research Watershed near Danville, Vermont is 8.42 km² in area, with an elevation range from 346 to 694 m above mean sea level (a.s.l). The study incorporates streamflow and temperature data for the years 1969—1974 from Anderson et al. (1977), and radiation measurements from the former NOAA-ARS Snow Research Station, now operated by the US Army Corps of Engineers Cold Regions Research and Engineering Laboratory (Hardy, 1994). The two versions of SRM were run in simulation mode for the melt season, March through May, of each year. Because of its small size, this basin was treated as a single HRU, and was not subdivided by elevation or aspect.

The time series of the degree-day coefficient a for the Temperature Index simulations varied from month to month, and from year to year; for example, a ranged from 0.3 in March to 0.55 in May in 1969, and from 0.4 in March to 0.55 in May in 1974. By contrast, in the Radiation/Temperature version, a constant value of $a_r = 0.2$ was applied for all years. Brubaker et al. (1996) describe the W-3 simulations in more detail. As discussed in that paper, the restricted degree-day coefficient a_r is actually variable in time and could, in principle, be estimated on a daily basis if the meteorological data were available. However, because the new version is being designed with a view toward use in forecasting and prediction (in which the necessary information would probably not be available), a constant value of a_r, representative of melt-season conditions, is applied.

Dischma, Switzerland

The Dischma basin lies in the Alps, near the town of Davos, Switzerland. It is 43.3 km² in area, with an elevation range of 1668—3146 m a.s.l. Detailed meteorological data from the nearby Weissfluhjoch research station (elev. 2693 m a.s.l.; near, but not in, the Dischma basin) allowed fairly accurate estimation of net radiation. Using a geographical information system (GIS), the basin was subdivided into three elevation zones, each further subdivided by aspect along the major axis of the basin into Northeast- and Southwest-facing classes, for a total of six HRUs. Ten melt seasons, 1970 through 1979, were simulated using both versions of SRM.

In these simulations, the Temperature Index degree-day coefficient varied from as low as 0.35 on 1 April to as high as 0.60 on 31 July. The Radiation/Temperature version was first run with the coefficient a_r set to a constant value of 0.17, as determined in Brubaker et al. (1996). The meteorological records for this region showed a clear change in weather patterns during the spring, from a generally lower-pressure, stormy winter regime to a higher-pressure, calmer summer pattern. Based on the meteorological records, a second sequence of a_r was computed: $a_r = 0.37$ for the first 45 days (to mid-May) and $a_r = 0.17\$$ for the remainder of each simulation. The Radiation/Temperature runs were repeated using this seasonal a_r sequence.

Rio Grande, Colorado, USA

The upper Rio Grande basin (above the stream gage at Del Norte, Colorado) is 3419 km² in area, with an elevation range of 2432—4215 m a.s.l. For this study, all the meteorological information necessary to estimate the terms of the net radiation index were retrieved from public sites on the World Wide Web. Using a GIS, the basin was subdivided into three elevation zones, further divided into South- and North-facing aspect classes, for a total of six HRUs. The melt season of 1984 was simulated by both versions of SRM. Former analysis of this large basin provided values of the Temperature Index degree-day coefficient a that varied among elevation zones, as well as within the melt season, ranging from

0.32 to 0.59. For the Radiation/Temperature version, a representative constant a_r = 0.18$ was applied to all HRUs throughout the season.

Results

The results of the W-3 (Sleepers River, Vermont) study are summarized in Table 1. In two of the six years, the Radiation/Temperature version improved the coefficient of determination by up to 0.07 (1969). In all six years of the Sleepers River study, the volume difference D_v is significantly decreased in the Radiation/Temperature version, with respect to the Temperature Index runs, which consistently underestimated seasonal flow. The Radiation/Temperature version appears to capture the early part of the 1969 melt season slightly better than the Temperature Index version (Figure 1). In the other years, R^2 decreases, by 0.11 in 1973, but only slightly in 1974. The runoff in 1973 was largely due to rainfall rather than snowmelt; and that year represents the worst performance by both versions (Figure 2).

The model accuracy criteria for the three sets of Dischma simulations appear in Table 2. By the R^2 measure, the constant-a_r Radiation/Temperature method performs as well as the Temperature-Index in three years (1974, 1976, and 1979), but worse in the remaining years. The constant-a_r tests consistently underestimate the total seasonal flow, as shown by the D_v results. Using a higher a_r for the first 45 days of the season in the Radiation/Temperature version improves the coefficient of determination by 0.09 and 0.12, respectively, in 1973 and 1977; however, the R^2 values are greatly reduced with respect to the constant-a_r case in 1971 and 1976. In the remaining six years, the seaonal a_r causes a modest improvement over the constant a_r; in 1974 and 1979, the seasonal-a_r Radiation/Temperature method out-performs the Temperature Index method, by the R^2 measure. The volume errors, D_v, are slightly less biased for the seasonal-a_r runs than for the constant-a_r; there are some negative values, indicating overestimation of the seasonal flow, but the average volume error is still positive (5.5 %). Hydrographs for the 1974 and 1977 melt seasons are presented as examples. Both versions of SRM capture the general shape, but not the details, of the hydrograph. In 1974, the best performance of the Radiation/Temperature version (Figure 3), the higher a_r moves the model hydrograph closer to the observed early in the season. The difference between the constant-a_r and seasonal-a_r runs persists for almost a month beyond the convergence of the a_r time series on day 45, due to the runoff recession parameterization. The Temperature Index model captures the runoff peak at day 67, but slightly overestimates daily flow after that date. The 1977 simulation (Figure 4) was the worst for the constant-a_r Radiation/Temperature method, and showed the most improvement in going from the constant to seasonal a_r (0.12 gain in R^2, see Table 2). This improvement appears to result from better capturing the peak flow at day 35.

The 1984 hydrographs for Rio Grande are shown in Figure 5, and the performance criteria in Table 3. Except for large differences in flow during April and early May (days 5 through 40), the two methods give very similar results. The overestimation of the early-spring flow by the Radiation/Temperature method accounts for the lower R^2 and more negative D_v with respect to the Temperature Index version. Further analysis is required to determine whether the assumption of an equal a_r for all the zones is justified.

CONCLUSIONS

Users of the microcomputer Snowmelt Runoff Model may now choose between a simple Temperature Index method, or the slightly more complex Radiation/Temperature method, depending upon the available data. In addition to temperature and precipitation data, which are required by both methods, each method requires particular information. The Radiation/Temperature method requires either net radiation data

Table 1. SRM performance measures: W-3 basin

Year	R^2		Simulation over(-) or under(+) estimation of seasonal flow D_v (%)	
	Temp. Index	Rad./Temp.	Temp. Index	Rad./Temp.
1969	0.79	0.86	2010	
1970	0.84	0.79	19	-1.9
1971	0.91	0.93	5.8	0.66
1972	0.85	0.82	17	0.21
1973	0.63	0.52	12	3.4
1974	0.75	0.74	15	1.9
Mean (St. Dev.)	0.80 (.10)	0.78 (0.14)	15 (5.3)	2.4 (4.1)

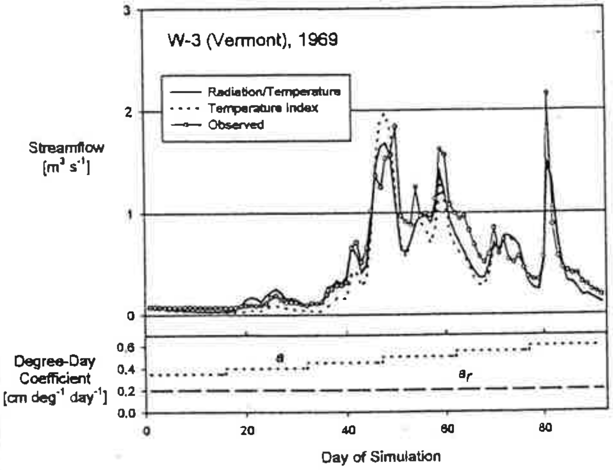

Figure 1. Observed and model-simulated runoff hydrographs for the W-3 subbasin of Sleepers River, Vermont, in 1969. The degree-day and restricted degree-day coefficients are shown at the bottom of the figure.

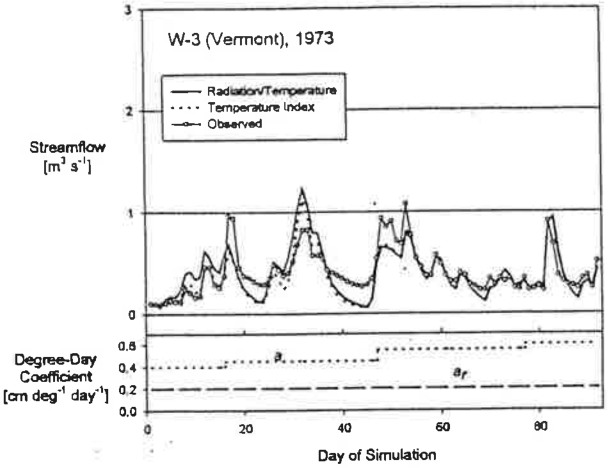

Figure 2. Observed and model-simulated runoff hydrographs for the W-3 subbasin of Sleepers River, Vermont, in 1973. The degree-day and restricted degree-day coefficients are shown at the bottom of the figure.

Table 2. SRM performance measures: Dischma Basin

Year	R^2			Simulation over(-) or under(+) estimation of seasonal flow D_v (%)		
	Temp. Index	Rad./Temp. (constant a_r)	Rad./Temp. (seasonal a_r)	Temp. Index	Rad./Temp. (constant a_r)	Rad./Temp. (seasonal a_r)
1970	0.94	0.86	0.87	6.7	19.5	15.47
1971	0.79	0.77	0.51	-0.4	6.7	-8.4
1972	0.85	0.83	0.85	-1.4	6.3	2.6
1973	0.85	0.75	0.84	1.8	16.0	8.9
1974	0.90	0.90	0.92	-4.2	9.9	6.1
1975	0.87	0.84	0.86	-1.1	12.2	6.7
1976	0.84	0.84	0.62	-5.3	4.2	-9.1
1977	0.81	0.64	0.76	2.5	20.1	14.8
1978	0.87	0.83	0.84	0.8	7.8	6.1
1979	0.84	0.84	0.87	0.9	14.4	12.1
Mean (St. Dev.)	0.86 (0.04)	0.81 (0.07)	0.79 (0.12)	0.0 (3.4)	11.7 (5.6)	5.5 (8.6)

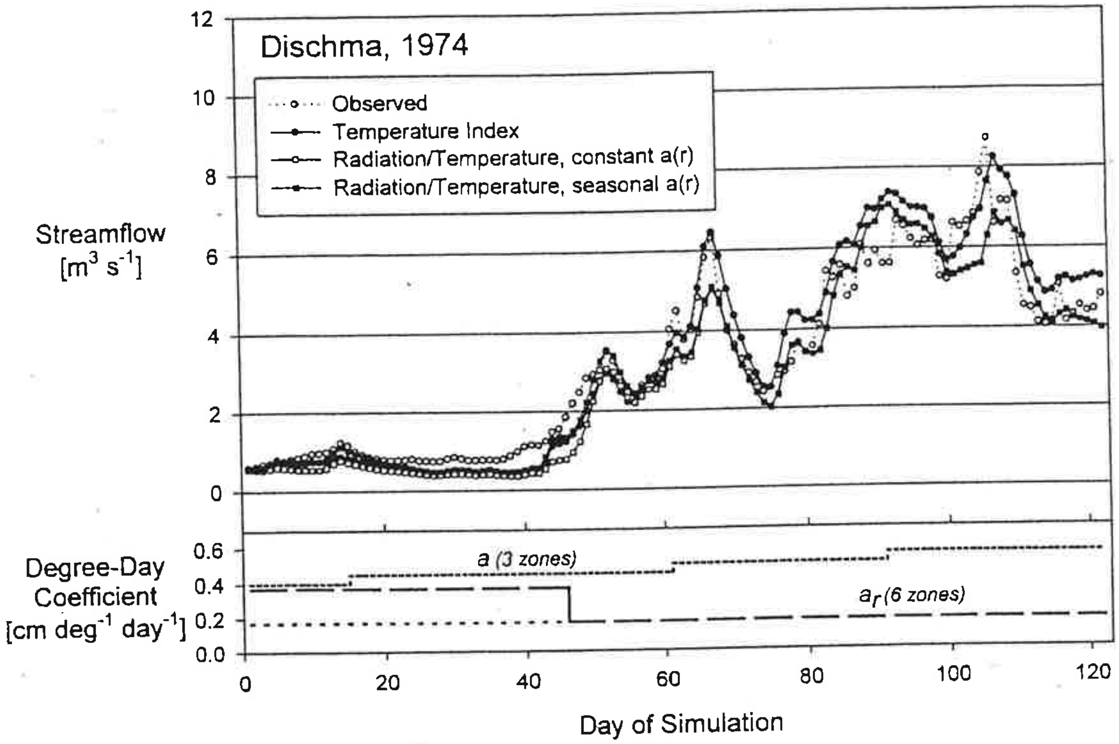

Figure 3. Observed and model-simulated runoff hydrographs for the Dischma basin near Davos, Switzerland, in 1974. The degree-day and restricted degree-day coefficients are shown at the bottom of the figure.

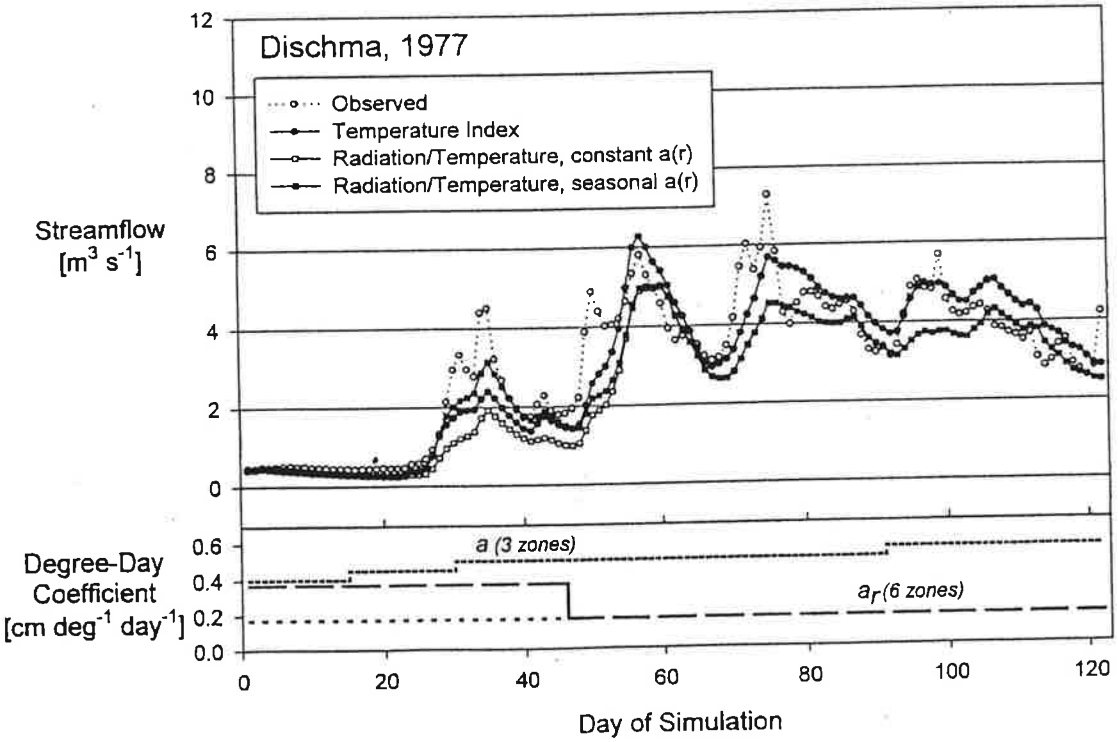

Figure 4. Observed and model-simulated runoff hydrographs for the Dischma basin near Davos, Switzerland, in 1977. The degree-day and restricted degree-day coefficients are shown at the bottom of the figure.

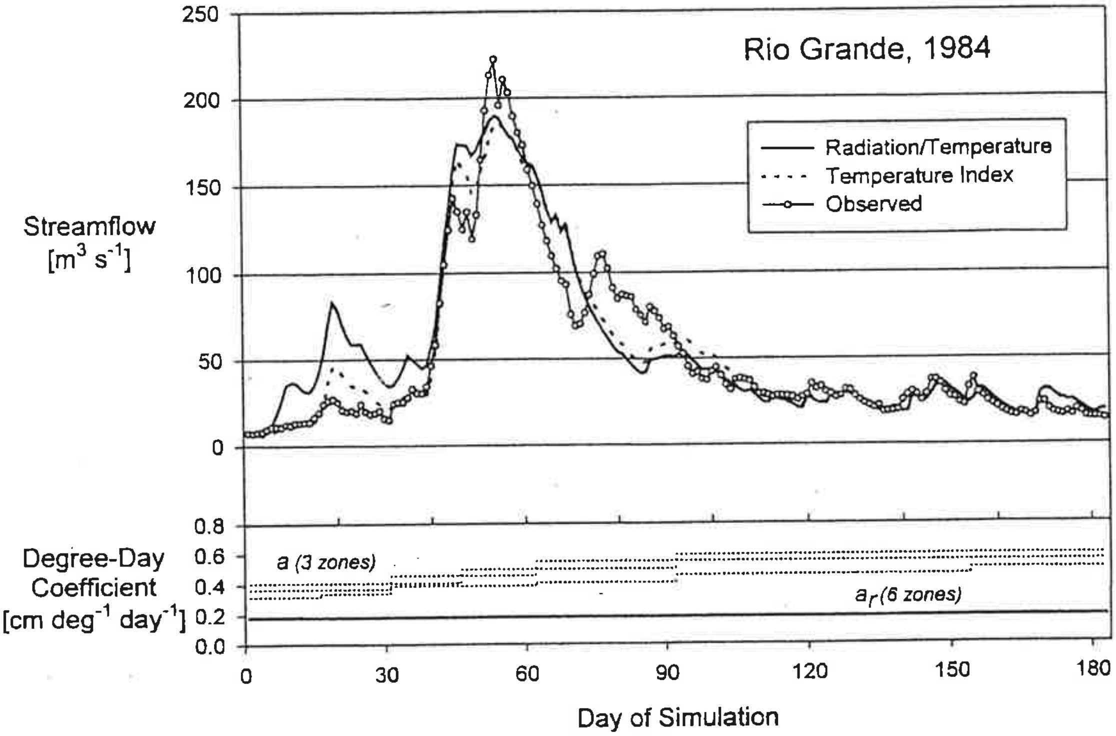

Figure 5. Observed and model-simulated runoff hydrographs for the Rio Grande at Del Norte, Colorado, in 1984. The degree-day and restricted degree-day coefficients are shown at the bottom of the figure.

Table 3. SRM performance measures: Rio Grande above Del Norte

Year	R^2		Simulation over(-) or under(+) estimation of seasonal flow D_v	
	Temp. Index	Rad./Temp.	Temp. Index	Rad./Temp.
1984	0.92	0.87	-1.1	-5.8

or meteorological inputs from which net radiation can be estimated; these data may not always be available for a given region. The Temperature Index method requires measurements or forecasts of snow density in order to estimate the degree-day coefficient, whereas the restricted degree-day coefficient in the Radiation/Temperature method can be estimated from meteorological data or forecasts.

The numerical results suggest that the two different models are comparable in terms of accuracy. In the Dischma test cases, the subdivision of the basin into Northeast- and Southwest-facing, rather than North- and South-facing, aspect classes may account for the consistent underestimation of seasonal streamflow. Because the HRU is assigned its average orientation in computing radiation, south-facing slopes are treated as either SW- or NE- facing in this arrangement and their radiative energy supply is underestimated. By contrast, the Rio Grande basin was subdivided between North and South, and the Radiation/Temperature method results are in better agreement with the observed runoff, probably because the computation of radiation to truly south-facing slopes gave a better estimate of the energy input to the basin as a whole.

The possibility of replacing the time-varying Temperature-Index degree-day coefficient a with a constant restricted degree-day coefficient a_r in the Radiation/Temperature version represents an improvement from an operational point of view, effectively reducing the dimension of the parameter space. In addition, the Radiation/Temperature restricted degree-day coefficient a_r may be estimated from routine meteorological measurements, and does not require snow density measurements — an advantage of the Radiation/Temperature method in regions where snow survey data are sparse in time and space. The Rio Grande study demonstrates that good results can be obtained with publicly-available meteorological data, not only with research-quality measurements as applied in the Dischma study.

The 1977 Dischma simulation was used as the starting point for an investigation of the effects of climate change on the timing of melt-season runoff in this basin (Brubaker and Rango, 1996). That study showed that, if changes in cloud type were to accompany a warming trend, these changes could either exacerbate or compensate for the effects of higher temperatures, depending on the direction and magnitude of the cloud-type changes. Because it accounts for the effect of clouds in the energy available for snowmelt, the Radiation/Temperature version is therefore potentially more useful than the simple Temperature Index version for water resources forecasting under conditions of climate change.

The new version of SRM and its documentation are being prepared for release, and further tests are underway. Interested individuals are encouraged to contact the authors.

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